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DECONFINEMENT IN THE BARYON RICH REGION

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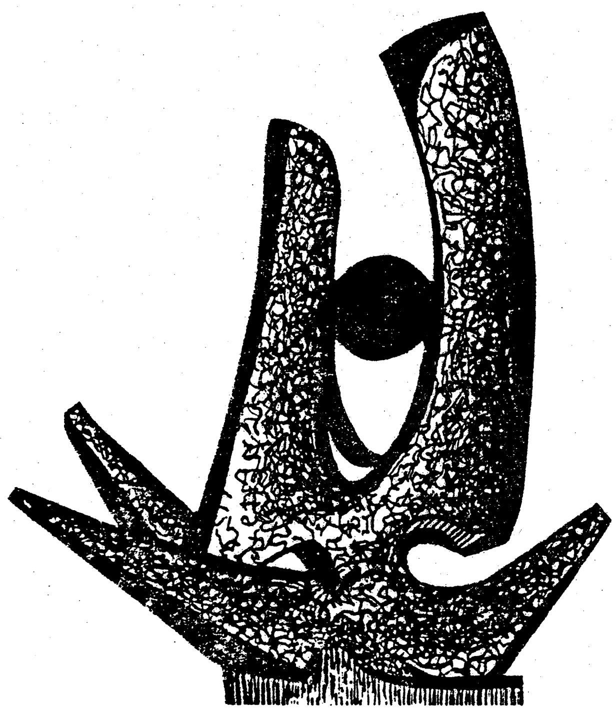

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Deconfinement in the Baryon Rich Region

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Abstract: The dynamics of deconfinement and hadronization at high chemical potentials, i.e. in baryon rich matter, are discussed. Quark gluon plasma formation in the fragmentation regions is characterized by low temperatures. Condensation discontinuities are predicted which result in substantial entropy production during hadronization in the fragmentation regions, by far exceeding the entropy expected if deconfinement would not occur. This excess entropy may be useful for plasma diagnostics, since it is directly related to the coupling strength and nonperturbative effects in the deconfined phase. Energy densities of 1 - 2 GeV/fm^3 are obtained in stopping collisions of heavy nuclei at bombarding energies E_{lab} = 5-10 GeV/n.

A transition from the deconfined quark-gluon plasma phase to confined color singlet states has (probably) occured during the rapid expansion of the early universe. Temperatures were very high but the net baryon charge was small. Therefore one can assume zero baryon chemical potentials in calculating the thermodynamic properties of strongly interacting matter in the early universe. It is sought to re-establish these conditions and thus enable a study of quark deconfinement in the laboratory via nuclear collisions at ultrarelativistic energies, $E_{c.m.} > 20$ GeV/N.[1,2]

Conjectures that a quark-gluon plasma can be formed in the central rapidity regime of nuclear collisions rely on the extrapolation of the experimentally observed mid rapidity gap in proton proton collisions. These data indicate that the mid rapidity region has net baryon numbers close to zero.[3,4] Hence, if nucleons in nuclei behave like free nucleons, nuclei should become transparent at high energies and a clear kinematic separation between the baryon rich fragmentation regions of projectile and target is expected.[5,6]

The mid rapidity region in this scenario would be filled with a plasma of quark-antiquark pairs as well as gluons, which condensate into a pion and nucleon-antinucleon plasma during the expansion. The energy densities attainable in both the central[5] as well as the fragmentation[6] regions have been estimated to be 1-2 GeV/fm³. This range of values coincides with the energy densities at which the deconfinement transition is predicted by SU(N) Yang Mills theory (pure gluon matter) on the lattice.[7] The Monte Carlo data indicate a first order phase transition at temperatures of about T = 190 MeV and zero baryon density.

Some recent developments may force us to modify this scenario substantially: Recent studies of 100 GeV proton induced reactions on heavy nuclei indicate a longitudinal momentum transfer to the leading proton which is substantially higher than expected from proton proton data.[8] The average rapidity loss of a 100 GeV proton in a lead nucleus is found to be $\Delta Y=2$, rather than $\Delta Y=0.7$ as observed for proton proton reactions. This would mean that a large fraction of the incident nucleons may be stopped in the center of momentum frame upon impact if heavy projectile and target nuclei are used.

Recent calculations based on the inside out cascade yield additional discouraging results for the baryon free midrapidity scenario: A strong leakage of baryons into the midrapidity region has been observed in the one dimensional hydrodynamic calculation with a consistent treatment of the hadron producing source terms.[9] Baryon number densities as high as 2/3 of normal nuclear matter density are obtained at mid rapidity; even higher densities are predicted at rapidities closer to the projectile and target.

Hence we may be forced to infer that a zero chemical potential plasma cannot be formed in nuclear collisions at energies $E_{lab}=100$ GeV/N. Then one would have to deal with a baryon rich plasma at all rapidity values. Unfortunately, theoretical information about the high density (high chemical potential) region is very limited. Lattice QCD calculations of the thermodynamic properties of a plasma containing light quarks are hampered by severe theoretical difficulties: The introduction of fermions on the lattice is at this time only feasible in the quenched approximation, i.e. quarks have to aquire a large mass $M_q \gg T_c$ so that the hopping parameter ($1/M_q$) expansion converges.[10] The situation of interest here, a plasma of light quarks and antiquarks plus gluons, can therefore not be studied to date. Furthermore, inclusion of fermions requires that the charge and baryon number assume integral values for color singlet states. These problems have been studied but so far without success.[2]

The behavior of confined (hadronic) matter can be described by an effective relativistic field theory of strongly interacting matter.[11] This approach has been applied successfully to describe known properties of nuclei and nuclear matter. This theory, though developped for normal nuclear systems, may turn out very useful for a phenomenological approach to the phase transition[12]: A sharp rise is observed for zero chemical potential in the energy density e/T^4. It occures at a critical temperature T_c = 190 MeV. In fact, the theory exhibits[12] a phase transition quite analogous to the one observed for SU(2) and SU(3) Yang Mills theory on the lattice; the order of the phase transition depends on the strength of the coupling constants. Furthermore, chiral symmetry is restored in this theory just above the critical temperature. The theory does not incorporate deconfinement, though.

Hence, a different approach is necessary for a study of the deconfined quark phase and an approach to the transition region from above: The thermodynamic properties of a plasma of light quarks and gluons at finite μ and T can be obtained from perturbative QCD,[13-16] but sizable nonperturbative corrections must be made. For zero temperature, the thermodynamical potential includes a perturbative expansion P_{pert} in α with terms up to order $\alpha^2 \ln\alpha$, a vacuum pressure contribution Λ_{vac} and an instanton term P_{inst} which takes non-perturbative effects partially into account.[16]

$$P = P_{pert} + P_{inst} - \Lambda_{vac} \,.$$

$$P_{pert} = n_f \frac{\mu^4}{4\pi^2} \left[1 - \frac{2\alpha}{\pi} - \frac{\alpha^2}{\pi^2} \left(n_f \ln(\alpha n_f) - .74\, n_f + 7.78\right)\right]$$

$$P_{inst} = \frac{8}{3} C \,\Lambda_{vac}\, n_B^{-5/3}$$

where n_f and n_B are the number of quark flavors and baryon density, respectively and C=1000 MeV fm^5. The dilute instanton gas term increases the pressure substantially, which results in a large decrease in the energy per baryon. In fact, the energy per baryon of the quark phase falls below the nucleon mass for a wide range of densities. Therefore we omitted this term from the calculation. The thermodynamical potential of a finite temperature plasma at nonzero chemical potential has been calculated up to third order[15] in $g = (4\pi\alpha)^{\frac{1}{2}}$

$$-\Omega = P = \frac{8\pi^2}{45} T^4 + \frac{7\pi^2}{60} n_f T^4$$

$$+ n_f \left(\frac{1}{4\pi^2} \mu^4 + \frac{1}{2} T^2\mu^2\right) - g^2 \left(\frac{T^4}{6} + \frac{5 n_f T^4}{72} + \frac{1}{8} n_f \left(\frac{\mu^4}{\pi^4} + \frac{2\mu^2 T^2}{\pi^2}\right)\right)$$

$$+ \frac{2}{3} \frac{g^3}{\pi^4} T \left(\pi^2 T^2 + \frac{1}{2} \sum_f \int_0^\infty \frac{dp}{E_p} n_p (p^2 + E_p^2)\right)^{3/2}$$

The g^3 term in this expansion corresponds to the plasmon term in Quantum electrodynamics. For small temperatures, it does not converge to the zero temperature perturbation expansion. On the contrary, this term contributes a finite entropy

$$S(T=0) = d\Omega/dT = \text{const}\cdot\mu^2$$

to the system even at zero temperature. Furthermore, its contribution to the energy per nucleon, which is zero (as it should be) for zero temperature, is large and negative for finite temperatures. In fact, the excitation energy per baryon is decreasing with increasing temperature. Because of this unphysical behavior we have omitted the plasmon term from the further calculations.

Following renormalization group arguments, the running coupling constant α can be written as

$$\alpha = \frac{4\pi}{11 - \frac{2}{3} N_f} \frac{1}{\ln M^2/\Lambda^2_{MOM}}$$

where N_f is the number of quark flavors involved, M is the effective momentum scale in the matter and Λ_{MOM} is the scale fixing parameter of QCD. The effective momentum scale is estimated to be:

$$M^2 = \frac{4}{3} \sum_i \frac{n_i \langle \vec{p}^2 \rangle_i}{\sum_i n_i}$$

where the sum is over all the constituent species present, each with a number density n_i. $\langle \vec{p}^2 \rangle_i$ is the thermal average of the three momenta of species i. In the case of massless quarks, the above formula reduces to:

$$M^2 = \frac{4/3(16 \int_0^\infty dp p^4 N_p + 6 \sum_f \int_0^\infty dp p^4 n_p}{16 \int_0^\infty dp p^2 N_p + 6 \sum_f \int_0^\infty dp p^2 n_p}$$

where

$$n_p = \frac{1}{e^{(P+\mu)/T}+1} + \frac{1}{e^{(P+\mu)/T}+1} \quad , \quad N_p = \frac{1}{e^{P/T}-1}$$

The Bose integrals are evaluated using the identity:

$$\int_0^\infty \frac{Z^{x-1}}{e^z-1} dz = \Gamma(x)\zeta(x) \quad x>1$$

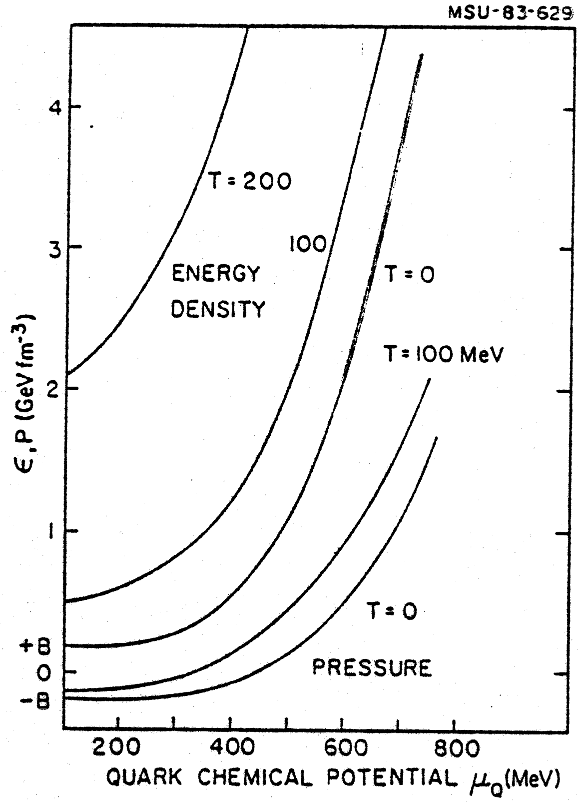
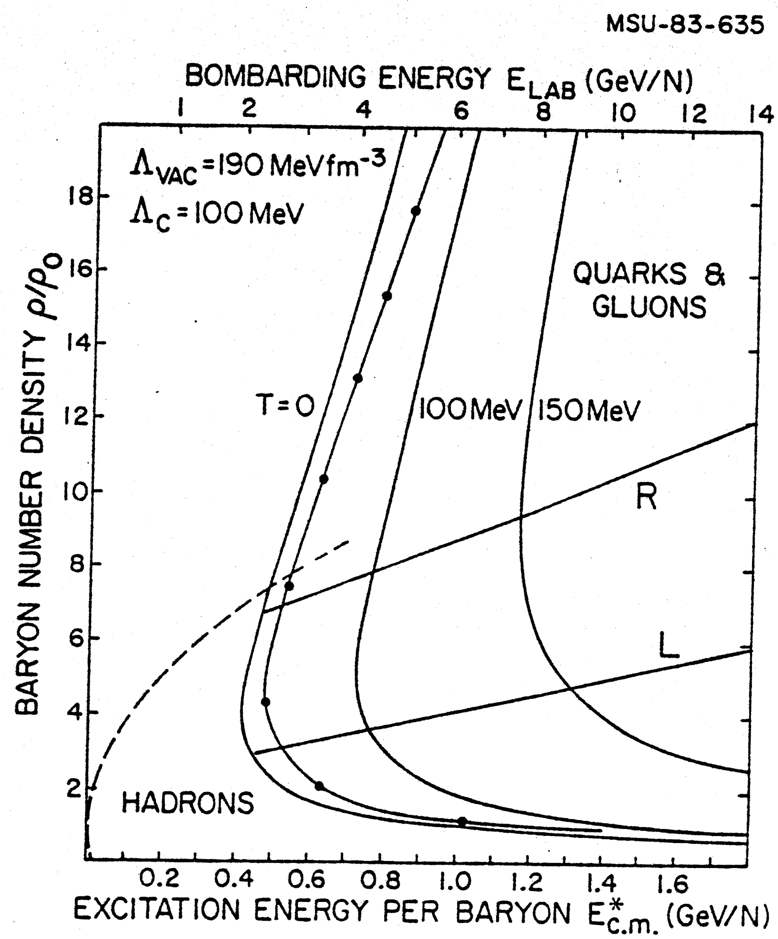


FIGURE 1
Energy density and pressure of the deconfined phase are shown as a function of the quark chemical potential μ_Q for temperatures $T = 0$, 100, 200 MeV.

FIGURE 2
The excitation energy per baryon needed to form the deconfined phase is plotted versus the baryon density ρ/ρ_0 for $\Lambda_{VAC} = 190$ MeV fm^{-3} and $\Lambda_{MOM} = 100$ MeV and $T =$ 0, 100, 150 MeV. The dotted line gives the $O(\alpha^2 \ell n\alpha)$ result for $T = 0$. The dashed line indicates normal nuclear matter. The lines labeled R and L represent the result of a combustion[21] and fireball calculation, respectively. The incident energy for these is given on top of the figure.



where Γ is the factorial function and ζ the Riemann zeta function. The Fermion integrals for arbitrary chemical potential and temperature yield

$$M^2 = \frac{4}{3}\,\frac{(16\cdot 4!\zeta(5)T^5+6\sum_f \int_0^\infty dpP^4 n_p}{(16\cdot 2\cdot\zeta(3)T^3+6\sum_f\int_0 dpP^2 n_p)}$$

They can be solved analytically for the limiting case T=0 and μ=0 only. For T=0

$$M^2 = \frac{4}{5}\,P_F^2$$

For μ=0

$$M^2 = 15.622T^2.$$

For finite μ and T we have evaluated the integrals numerically. It is interesting to note that the numerical result can be approximated by

$$M^2 = 4/5\ \mu^2 + 15.622T^2$$

This expression agrees to within a few percent with the correct result. This theory therefore has two free parameters, namely the scale fixing parameter Λ_{MOM} and the energy density of the real vacuum Λ_{VAC}. Λ_{MOM} and Λ_{VAC} can be determined by adjusting the pressure and energy density calculated in this approach at zero chemical potential to SU(N) Yang Mills Monte Carlo data. One obtains[17] a surprisingly good agreement for Λ_{MOM}=100 MeV and Λ_{VAC}=190 MeV/fm^{-3}. We have adopted these values as reference parameters for most numerical calculations presented here; we also study the dependence of the numerical results on these parameters.

The energy density e, entropy density s, and baryon number ρ of the deconfined quark gluon phase are obtained from the thermodynamical potential via

$$e = -\mu\,\frac{\partial\Omega}{\partial\mu} - T\,\frac{\partial\Omega}{\partial T} + \Omega$$

$$s = -\,\frac{\partial\Omega}{\partial T}$$

$$\rho = -\,\frac{1}{3}\,\frac{\partial\Omega}{\partial\mu}$$

The pressure p and energy density e of the plasma are shown in Fig. 1 as a function of the chemical potential for T = 0, 100 and 200 MeV. e and p tend towards $\pm B_{vac}$, respectively for $\mu \to 0$. The running coupling constant exhibits, however, a pole at chemical potentials on the order of 100 MeV, so the curves can not be continued below this value of μ. It is interesting to note that this chemical potential corresponds to zero baryon number density. Hence, the unphysical pole in the coupling constant can be avoided by plotting the thermodynamic variables as a function of the baryon number density ρ.

Figure 2 shows the energy per baryon $E/A = e/\rho$ of the deconfined phase vs. the net baryon number density. A typical curve for normal nuclear matter is also shown. Quark matter is apparently energetically disfavoured compared to ordinary nuclear matter: The minimum energy per baryon of the deconfined phase is about 1.34 GeV, i.e. at an excitation energy per baryon 0.4 GeV higher (for Λ_{MOM}=100 MeV and Λ_{VAC}=190 MeV/fm^3) than the ground state of nuclear matter. Only at densities $\rho > 8\ \rho_0$ would the deconfined state be energetically favorable compared to confined matter at the same density.

The energy density at the crossing of the two equations of state is (1.4 - 1.8 GeV/N)$\cdot$(0.6 - 1.2 baryons per fm^3) = 0.8 - 2.2 GeV/fm^3, hence in the same bulk part as the critical energy density obtained from Monte Carlo data at μ=0. The energy per particle depends on the choice of Λ_{VAC} and Λ_{MOM}. The energy gap is 0.9 GeV/N when Λ_{VAC} is increased to 450 MeV/ fm^3. These excitation energies may well be achievable in the fragmentation region of ultrarelativistic nuclear collisions.[2,6]

We want to point out that the perturbation expansion $O(g^2)$ and $O(g^4 \ln g)$ equations of state differ by less than 5% - the running coupling constant is $\alpha < 0.6$ throughout the density region of interest. From the energy gap between ground state nuclear matter and the deconfined phase one can estimate the minimum bombarding energy necessary to form the deconfined state in a stopping collision of heavy nuclei. This minimum energy depends on the choice of Λ_{VAC} and Λ_{MOM}. One finds

$$E_{lab}^{min} = 2\ M_N((E + M_N)/M_N)^2-1)=$$
$$= 2 \text{ GeV/N for (for } \Lambda_{MOM} = 100 \text{ MeV and } \Lambda_{VAC} = 190 \text{ MeV/fm}^3)$$
and
$$= 4 \text{ GeV/N for (for } \Lambda_{MOM} = 200 \text{ MeV and } \Lambda_{VAC} = 450 \text{ MeV/fm}^3).$$

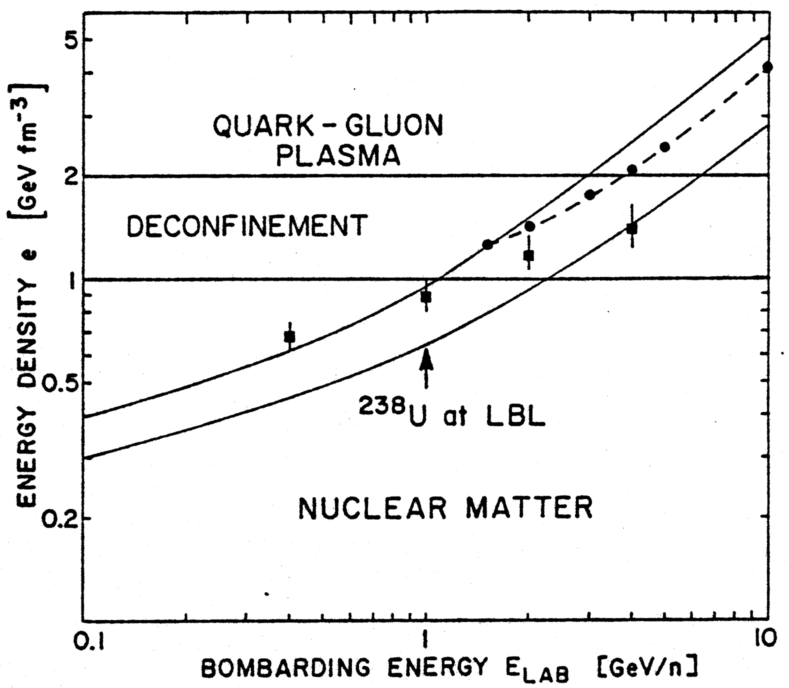
These estimates represent, of course, lower limits only. In a realistic scenario for a nucleus nucleus collision entropy is produced and the finite temperature effects become significant.

The dependence of the energy per baryon on the temperature is depicted in Fig. 2. Since the energy density increases as T^2, a T = 200 MeV plasma is achievable only at the expense of very high excitation energy $E_{c.m.}$>1.8 GeV/N.

A consistent treatment of the dynamical evolution of nuclear collisions which includes a description of the entropy generation is provided by the hydrodynamical model.[18] There is experimental evidence[19] for hydrodynamic behavior at BEVALAC bombarding energies - nuclear matter exhibits the sidewards flow features predicted by the hydrodynamic calculations[18,20]: Nuclear fluid dynamics predicts a peak in the angular distributions of the flow tensors for collisions of equal nuclei, which shifts to larger angles with increasing multiplicity. This is in agreement with recent experimental data on collisions of Nb with Nb at 0.4 GeV/N observed in the Plastic Ball 4π detector system.[19] In the following we assume[21] that hydrodynamics is also valid at higher energies, E_{lab} > 1 GeV/N. This extrapolation is questionable at very high energies, E_{lab} > 20 GeV/N, because of the longitudinal growth which may lead to the 'transparency' predicted by the inside out cascade.[3,4,22] Fig. 3 shows the result of our hydrodynamic calculations of the energy densities attainable in central collisions of heavy nuclei. Observe that the energy density obtained depends on the equation of state (EOS) used in the calculation. The different types of EOS include a Hagedorn hadron gas with an exponentially increasing mass spectrum and a deconfined quark gluon plasma. The different EOS lead to prediction of a regime of bombarding energies at which the 'critical' energy densities, e = 1 - 2 GeV/fm³, may be reached: E_{lab}^{crit} = 4-7 GeV/N, values surprisingly modest compared to the values E_{lab} > 100 GeV/N considered to be necessary to form the baryon free plasma. These are the initial energy densities in the collision. The system will subsequently expand as a result of the high pressure buildup. Hence the matter is accelerated, the density diminished and, because of energy conservation, the internal energy and temperature drop. If the matter in concern is a system of colorless, confined hadrons, this gas expands into the vacuum until it's density, pressure and temperature - and it's speed of sound - reach zero. Such an ordinary rarefaction wave leads to a large acceleration of the system, since the total internal energy gets transformed into collective kinetic energy of expansion.

The dynamical path of a collision in the ρ-T plane, the phase diagram of hadronic matter, is depicted in Fig. 4. The initial stage of high compression and excitation is followed quickly by the isentropic expansion of the system. The matter cools only modestly during the dense stage where baryon densities exceed normal nuclear density. At densities below normal density, the system is cooled much more rapidly due to the formation of pions. Also shown in the figure are contours of constant energy densities of 1 and 1.5 GeV/fm³ of the deconfined phase. Observe that according to the present calculation bombarding energies E_{lab} > 2-4 GeV/N could be sufficient for deconfinement to

FIGURE 3
The energy density obtained from the present hydrodynamical model is shown vs. the bombarding energy. Three different equations of state are used: Hagedorn gas, K = 100 MeV (upper curve), nucleon Fermi gas, K = 300 MeV (lower curve), and deconfined plasma of quarks and gluons (dash-dotted).



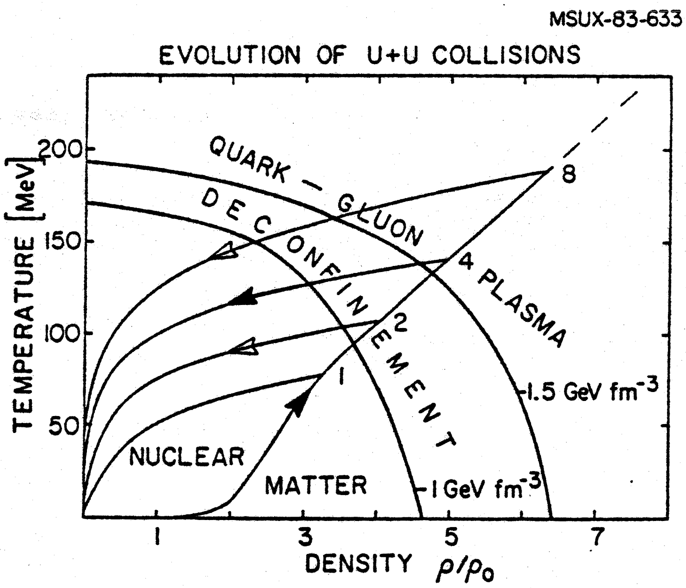
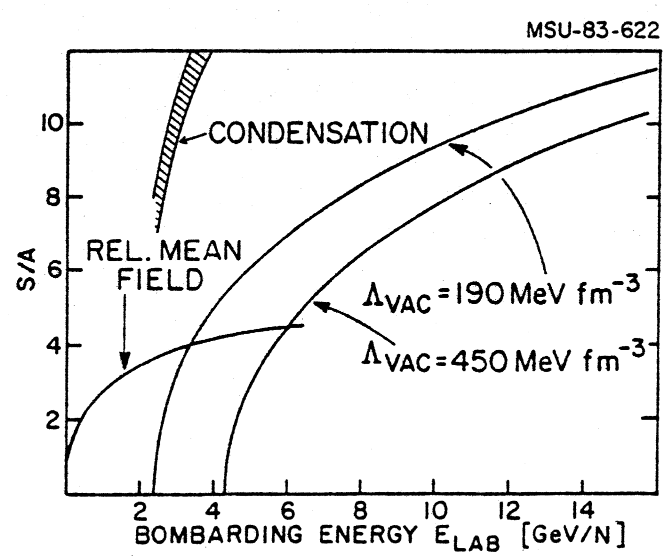


FIGURE 4
Dynamical path of nuclear collisions in the ρ-T diagram as obtained in the present hydrodynamical model. Arrows indicate compression (towards right) and subsequent expansion (to left) at E_{LAB} = 1, 2, 4 and 8 GeV/N for hadron matter. Critical energy density contours (ε = 1 and 1.5 GeV fm^{-3}) of plasma phase are also shown.

FIGURE 5
The entropy produced in the present hydrodynamic model is shown as a function of E_{LAB} for nuclear matter (labeled "mean field") and deconfined plasma phase with Λ_{MOM} = 100 MeV and different vacuum pressures Λ_{VAC}. Also shown is the large entropy excess produced by hadronization in the condensation discontinuity predicted here.



occur in stopping collisions. If deconfinement actually would occur at these rather modest energies, the energy gap between confined and deconfined matter would result in temperatures and entropies substantially lower than those calculated under the assumption that deconfinement does not happen. Fig. 5 shows the entropies calculated in the present hydrodynamic model assuming that deconfinement i) does and ii) does not occur. The plasma equation of state is used to calculate i) and Walecka's relativistic mean field equation of state is used for ii). The nuclear matter entropy exceeds 4 at E_{lab} > 2 GeV/N. The plasma entropy, on the other hand, is zero at the critical energy necessary to overcome the energy gap, E_{crit} = 2.2 and 4.2 GeV/N for Λ_{VAC}= 190 and 450 MeV/fm³, respectively. This mechanism of 'cold' plasma production has been discussed previously.[21-23]

It should be noted that none of the discussed possible experimental signatures for the deconfinement transition (dilepton-,[24] photon-,[25] strangeness[26] production) could work in this baryon rich region: These signatures rely on the very high temperatures predicted for the baryon free plasma, while at the same energy density the temperatures in the baryon rich plasma are much lower.

The plasma entropy increases very fast with the the bombarding energy as compared to the nuclear matter curve. This is due to the repulsive interaction in nuclear matter, in particular in Walecka's model, to be contrasted with the quark-gluon plasma which tends towards asymptotic freedom, i.e. less interactions, with increasing energy density. Hence, the entropy of the plasma phase would exceed the entropy of the confined phase after a transition domain in bombarding energy of about 2 GeV/N. The measurement of the entropy would thus provide an excellent signature for the onset of the deconfinement transition. It could also be very useful for plasma diagnostics because of it's sensitivity to the interactions.

Up to now we have not discussed what actully happens subsequent to the formation of the deconfined phase. We have assumed that the entropy stays constant after the initial excitation of the system. This is a reasonable assumption for the hadron matter equation of state until it reaches densities so low that thermal contact between the constituents ceases. Then there is a transition from the interacting gas to the free expansion of noninteracting particles, which may produce some additional entropy.[27]

The deconfined plasma phase, on the other hand, must undergo a transition to the confined hadron phase somewhere during the expansion. If the plasma expands isentropically[21] and cools, it soon becomes saturated. Upon further isentropic expansion the plasma becomes supersaturated and condensation begins.[21] Possibly the plasma expands until it reaches the

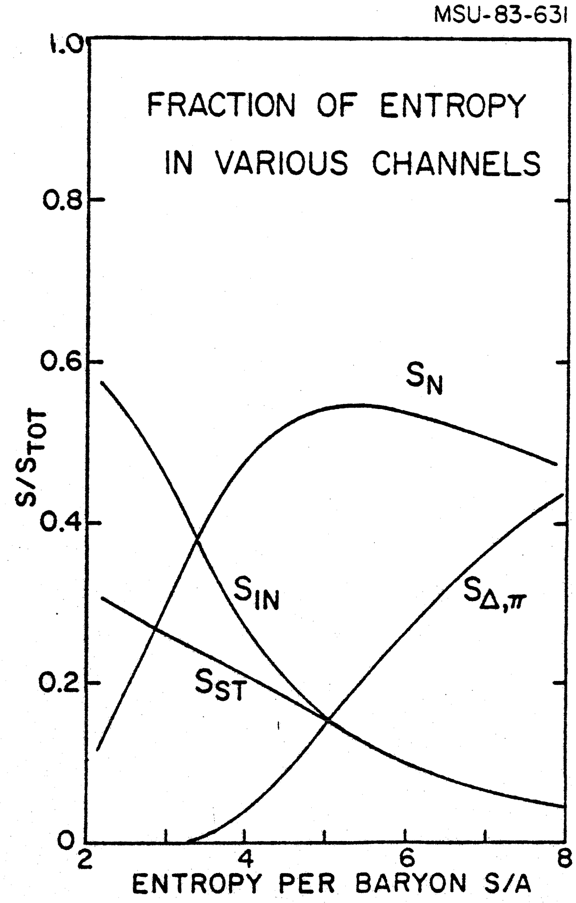


FIGURE 6
The fraction of entropy in various channels is shown as a function of the total entropy per baryon at the final breakup of the system ($\rho/\rho_0 = 0.5$). Result of a quantum statistical calculation.[20]

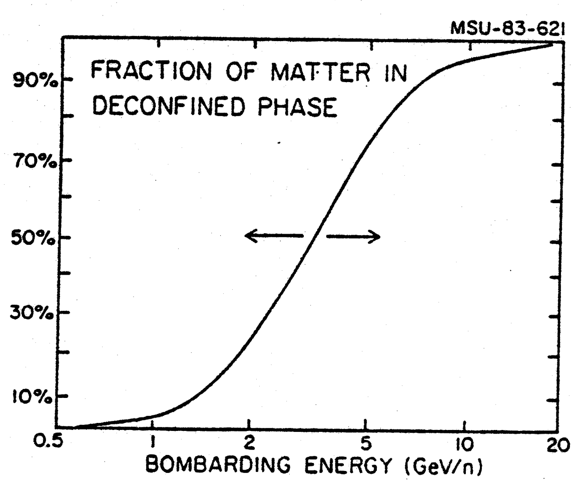


FIGURE 7
Fraction of matter in the deconfined phase as a function of the bombarding energy. Result of a percolation calculation.[21] Arrows indicate shift of curve with Λ_{VAC} and Λ_{MOM}.

minimum of the energy per nucleon isentrope, i.e. a zero pressure state, and then breaks up into hadrons.[21] The condensation centers in the pure supersaturated phase appear as the result of the agglomeration of quarks into colorless multiquark states (hadrons and hadron complexes).

A condensation discontinuity[28] develops at the transition from the quark phase into the hadron phase. A significant amount of entropy is produced in this condensation discontinuity. It stems from the latent heat (excitation energy) released when the gap energy (0.4 to 0.9 GeV/N) is set free upon recondensation. Conservation of momentum, (baryon) charge, and energy flow across the condensation discontinuity can be written as

$$\frac{\omega_1^2}{\rho_1^2} - \frac{\omega_2^2}{\rho_2^2} + (p_2-p_1)\left(\frac{\omega_1}{\rho_1^2} + \frac{\omega_2}{\rho_2^2}\right) = 0$$

where $\omega=e+p$ denotes the enthalpy and the indices refer to the confined and deconfined phase, respectively. The momentum transfer to the condensed phase can be computed via

$$v_{12} = \sqrt{\frac{(p_2-p_1)(e_2-e_1)}{(e_1+p_2)(e_2+p_1)}}$$

the relative speed v_{12} of the deconfined phase to the accelerated hadron phase. These are formally equivalent to the Rankine relations of the formation of shock waves. Physically they are completely different, since they describe the expansion from one phase into another one with different chemical and/or physical properties. Some part of the internal energy available is thereby transformed into kinetic energy of the material which is formed behind the condensation discontinuity. At bombarding energies close to the critical one the pressure in the deconfined phase is small. Then we can write[21]

$$W_H^2 - W_Q^2 + p\left(\frac{W_H}{\rho_H} - \frac{W_Q}{\rho_Q}\right) = 0$$

Solving for the excitation energy of the condensed hadron phase, W_H we can calculate the entropy produced in the condensation:

$$S = \sum S_i$$

where S_i is the specific entropy of the various hadronic species produced. The calculated entropy after condensation is depicted in Fig. 5. Observe the large jump from almost zero entropy in the deconfined phase just above the critical bombarding energy to S/A > 7 after recondensation. This increase in fact depends on the vacuum pressure and on the momentum cut off, hence it may be useful for plasma diagnostics. Naturally this threshold increase of S/A would serve as a unique signature for the deconfinement transition. In contrast to the signatures discussed previously, which all rely on the formation of a baryon poor high temperature plasma, this signature does not depend on getting information out of the primordial plasma state before it recondensates but it rather uses the unusual properties of the recondensed matter after the short lived initial state has decayed.

There is of course one additional question to be answered: How can one measure the entropy produced? Fig. 6 shows the abundance of various fragments as calculated using a quantum statistical model of fragment production, i.e. assuming thermal and chemical equilibrium can be established during a collision. At the entropy values of interest here, almost 90% of the emitted fragments are nucleons and mesons. Bound nuclei (in particular light fragments d, t, α) are, however, also produced. The ratio of bound nucleons to the total number of baryons present (i.e. bound and unbound nucleons and resonances) can give a measure of the entropy produced, as well as the total number of mesons (pions) created. Hence, there are two possible signals to search for the predicted increase of the entropy due to condensation.

Several complications make life more difficult than our scenario suggests. Perfect kinetic equilibrium, assumed in these calculations, may not be achieved during the collision, transparency may set in earlier than expected, or there may be a rather gradual change from the confined to the deconfined phase. The latter may be due to either a two phase equilibrium or due to slow percolation of the quarks. Fig. 7 shows the fraction of matter in the deconfined phase calculated[21] by assuming that supersaturated hadronic vapor may be formed, thru which quarks percolate. Observe the broad transition region, 2 - 7 GeV/N, where the fraction of deconfined matter would increase from 20 to 80%. Another point of critique on the above scenario is that it leaves out the additional entropy present in the hadronic matter due to the formation of nucleon and delta resonances and mesons (pions!). They contribute about 1 unit of S/A at 2.5 GeV/N bombarding energy. The crucial assumptions are, however, those of short time scales for thermalization and chemical equilibration.

In conclusion, an experimental study of collisions between heavy nuclei at energies E_{lab}=5-10 GeV/N can provide an important testing ground for possible deconfinement in the baryon rich region. In fact, conditions there may be more favorable than in the ultrarelativistic energy region.

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